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Development of Novel Transportation Shells for the Rapid, Automated Manufacture of Automotive Composite Parts

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Abstract

In this paper the feasibility of a new approach, whereby dry fibre composite preforms of shaped and organised plies are held together by an external polymer shell, is presented for the manufacture of fibre reinforced composite parts at high volumes and low cost. The polymer shell, as a transport vessel, is intended to rapidly provide the composite preform with the required geometric stability and form; so reducing the impact of the time consuming binder activation processes that are currently used in traditional Liquid Composite Moulding (LCM) techniques. Removal of the binder activation process may also improve the final part quality during resin infusion stages, by retaining the preforms' permeability, plus removing the inclusion of 'foreign' material not forming part of either the fibre or matrix systems. This paper presents the design of the new approach and its formulation; the development of understanding via lab-scale test machinery; results in terms of manufacturing capability - such as handling characteristics for pick and place automation, and mechanical performance of the presented LCM structures. Handling performance is particularly positive since better geometric stability and the easy formation of a vacuum seal between the robot head and the part is possible. The paper also presents a further novel development, whereby the transport vessels are retained as an integral element, providing the entire polymer matrix system for the final composite part. This enables further time and cost savings, replacing the need for the expensive LCM machinery that are currently utilised for rapid manufacture of composite parts.

Keywords: Composites; Preforming; Automation; Manufacture; Prehension

1. Introduction

The reduction of vehicle emissions is currently one of, if not the, biggest design drivers for the mass-produced vehicle market. In 1978, the fleet averaged emissions standard demanded by Corporate Averaged Fuel Economy (CAFE) legislation in the USA was 18mpg for light passenger cars, and over the next 30 years this has nearly doubled to a 35mpg target by 2020 [1]. European legislation requires vehicles to reduce output to 95g CO_2/km by 2020 (fleet averaged CO_2) [2].

For traditional internal combustion (IC) vehicles, Brooke and Evans show that a 10% reduction in weight translates to a 5-8% increase in fuel efficiency [3]. Meanwhile, for electric vehicles (EV), the increased weight of current generation battery and motor set-ups in comparison with combustion vehicles [4] means weight saving throughout the structure of the vehicle is key. In 2018, The UK released a "Road to Zero" strategy, mandating all new cars and vans to be effectively zero emission by 2040 [5]. This target has already moved to 2035. Providing the ability to manufacture light-weight vehicle structures at high volume is crucial, given a vehicle's primary structure is approximately 60% of its weight [6].

Today's modern targets and ever-mounting environmental concerns cannot be met with a similar overhaul in philosophy of design as was seen in the 1970s without also incorporating into this a large shift in the materials utilised. Table 1, adapted from work by Mallick [6], shows typical mass distributions by material in average automobiles.

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Table 1. Distribution of material in an average automobile (adapted from [6])

Material	Vehicle Weight %	Major Area(s)
Steel	55	Body and structure, engine and transmission
Cast Iron	9	Engine, brakes
Aluminium	8.5	Engine block and wheels
Copper	1.5	Electrics
Polymers and FRPs	9	Interior, bonnet
Elastomers	4	Tires, gaskets
Glass	3	Windows
Other	10	Interior, fluids

Since the early 1900s, steel has led the way in usage for the construction of automobiles. In comparison to other materials, its low cost, ease of formability and assembly and abundant supply gave it precedence [7]. Hall and Fekete [8] give several examples of how the integration of much lighter, advanced high-strength steel (AHSS) has been able to provide lighter, more efficient structures, however these are still limited in their structural potential.

Both aluminium and more modern, high-tech alloys have been investigated to replace steel. High strength aluminium alloys give exceptional specific strength but little stiffness improvement [9], whilst also having much lower formability [10] and three to four times the basic material cost of steel [6]. More modern, high-tech alloys include magnesium or titanium alloys and have even lower elemental densities [11]. However they have a significant cost, with the cost of titanium alloys being orders of magnitude higher than that of their steel or even aluminium counterparts [12], alongside severe corrosion issues and extremely poor formability [6].

Therefore, it can be argued that a step away from metals as the primary structure should be taken, instead embracing fibre-reinforced polymers (FRPs). These offer the best promise in terms of lightweighting and possess the greatest ability to allow the automotive industry to fight the growing environmental crises with lighter and more efficient vehicles. A key focus of this work is to allow for these new composite materials to be integrated into the current manufacturing chains of the automotive industry with as little disruption as possible, neither heavily increasing production times nor cost.

2. Automotive Composites: The Challenge

For mass-produced vehicles to be formed of fully composite structural components, new manufacturing processes must be further developed [13]. Low cost and high-volume manufacturing targets have been set out by the composites industry, aiming to "Develop the immediate market opportunities in High Volume, Low Cost manufacturing" [14].

Direct impregnation techniques, such as Resin Transfer Moulding (RTM), are favoured over the use of prepreg materials, allowing for cheaper materials and processes to be used, and the process to be split into distinct stages [15]. A key aspect is the creation of a preform before the impregnation. This provides the possibility to allow for dedicated equipment to be used for each process, increasing both the speed and cost effectiveness of each process, and is the key basis of any high-volume, automated assembly line.

Tackifiers, or binders, are utilised to stiffen the preform. This allows easier handling and helps protect the preform from geometrical defect generation during transportation [16], reducing the chance of costly tool damage and potential pausing of production.

However, binders present several problems. As shown in Figure 1 [17], binder activation and cooling take a large proportion of the total time of the manufacture of the part. Further, the inclusion of this added binder material into the final product provides a penalty on the quality of the overall part. The binder itself, as applied, is also believed to lower the permeability of the preform, either sitting between the tows and lowering the permeability of the preform and stopping the part from being fully wetted out, or in the case of high-heat, intra-tow binder, allowing good permeability between bound tows but almost no intra-tow impregnation [18]. As such, it can be seen that the removal of any form of chemical binder material from the preform would provide a great reduction in the time of the full manufacture process, as well as possible quality improvements in the finished part.

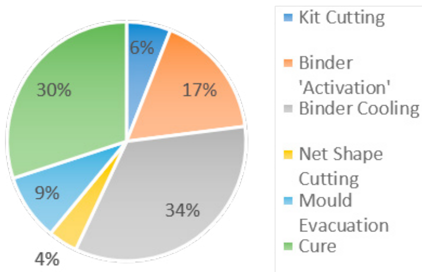

Fig. 1. Evaluation of the time cost of each stage of the fabrication of a simple automotive part manufactured utilising HP RTM [17]

Despite these challenges, demand is high, and the targets set out are challenging. In 2016, the Automotive Council, as part of the Composites Leadership Forum's UK Composites Strategy, set out several goals with regards to cost, rate and sustainability of automotive composites by 2025. The average weight of existing parts should reduce by 15%, but with typical costs per kg saved to not exceed £5, a typical takt time of 60 seconds and an end of life recyclability of greater than 85% with a material waste reduction of greater than 60% [14]. It can be seen, therefore, that in order to introduce composites into the industry on a wide scale and meet these targets, a significant step-change in the manufacturing process is required.

3. Current Industrial Concepts

The requirements for the formulation of a manufacturing process that will enable the realisation of large-scale composite material use within the industry can be summarised with three key design drivers. These are the time, cost and scalability of the process. The process must be driven by minimising both the cost of and the time taken, whilst allowing for it to be easily repeatable on a large scale, and maintaining parts of acceptably high quality.

Perhaps the most common high-volume manufacturing method currently is High-Pressure Resin Transfer Moulding (HP RTM). This is the technique which is utilised by BMW for the fabrication of the i3, the first mass produced, 'family/city car' whereby the majority of the chassis and structural body components are created from carbon fibre [13]. This allows for a cure cycle under 10 minutes [19], however several problems persist, such as large amounts of scrap generation and a lack of dimensional stability necessitating human intervention during the process [20]. This is alongside the well-documented drawbacks of HP and UHP RTM, such as tooling costs and uniform impregnation [21][22].

Wet compression moulding is a promising concept, whereby resin is applied to the dry fibre external to the press. The wetted fibre is then placed into a press, and pressing and curing takes place in the mould at this stage. This can lower costs due to the lack of expensive HP-RTM machinery and tooling, cure can be sped up, and parts at different stages of the process can be manufactured in parallel [23].

However, fundamental issues with the preforming of the dry material remain. Some form of binder or other preform stability must be used. Lowered permeability due to the binder is even more problematic here than with HP-RTM, as the higher injection pressures are not present, and lateral, inter-tow flow paths are not available. As such, utilising a similar technique without the need of an invasive, intra-lamina preforming aid would provide significantly greater promise.

4. Current Industrial Concepts

This study proposes a new concept to address the problems presented, termed the 'Clamshell' concept. This is an integrated thermoplastic preform stiffening system, with the aim of removing traditional binder material completely. Instead of the preform being stiffened and held in shape using a binder material, the preform is held in shape utilising an external thermoplastic shell. This protects the preform and holds its shape during transportation from the preforming to the infusion stations. Once at the infusion station, the shell can match perfectly with the tool face, and either be impregnated to become a component of the final piece, or ejected from the mould following the infusion process. This allows the preform to be delivered to the tool free from defects and geometric imperfections that can be imparted during transportation of preforms held together with traditional binder material. As such, not only are the disadvantages of binder material removed, but improved part quality and consistency is achieved. An initial feasibility study has been undertaken to demonstrate that this is a valid concept and impregnation can be achieved.

The preform will be formed as it is currently at an automated preforming station. However, this will be done inside a protective thermoplastic shell, holding the preform to shape. The shell can be formed prior to the fibre being placed inside, or simultaneously, depending on the variation of the concept utilised. The clamshell preform can be moved rapidly to the press using automated tools, becoming part of the total closed mould process, matched to the tool on both faces. The primary method under investigation is for the shell to be placed on a heated tool, melting the shell. This will then be pressed inside the closed mould under high pressure, allowing the material that previously formed the shell to impregnate the preform and form the matrix for the final composite material. Figure 2 shows a basic outline of the process.

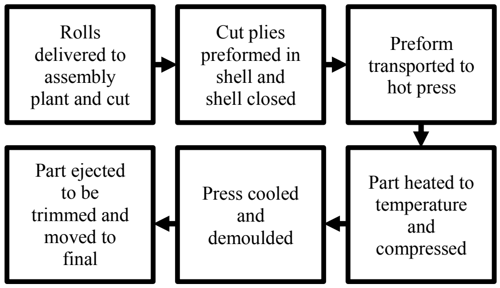

Fig. 2. Basic process diagram for the manufacture of the automotive components via the clamshell method.

4.1. Potential benefits and unknowns

A number of potential benefits may be gained using this technique ahead of processes such as HP RTM and wet compression moulding:

- Removal of binder material, lowering cycle time and improving part quality.
- Established thermoplastic forming process can be easily adapted to form the shells [24].
- Removal of the need for discontinuous fibres currently used in high-volume processing.
- Thermoplastics allow for fundamentally quicker manufacturing cycle times, alongside longer storage life and greater recyclability compared to thermosets.

Alongside the potential benefits, several unknown factors with regards to the feasibility and performance of this concept exist. These include the points listed below, with the work presented here beginning to tackle the first two points:

- Formation of shell – How simple will it be to form this? Can it be done with the fibre in-situ or added later? Will methods used for prototyping be suitable? How well can the geometry be met?
- Shell transportation – Will a significant improvement over traditional preforms be present? Can the shell better resist deformation, both during transport and if dropped?
- Part infusion – How can this be best achieved? What materials are most suitable?

4.2. Flexible, automated, and integrated manufacturing

The clamshell has the potential to vastly outperform traditional binder for preforming throughout the manufacturing process, including both manual handling and robotic pick-and-place systems. An external protective shell offers better protection than traditional binder materials, and thus increased resistance to damage or geometric changes. This allows consistent part manufacture and prevents potential damage to the expensive tooling that is possible if the preform becomes damaged and the shape changed, whilst also lowering initial tooling costs due to the removal of high-pressure injection.

The overall manufacturing stream is notably similar to the traditional sheet metal processing that is currently utilised for the fabrication of automotive components. The shell's rigid and non-porous nature means that the current pick and place systems utilised are still applicable, whilst the rapid impregnation method can be seen to be similar to the current stamp forming methods used for metallic components. As such, the overall manufacturing process is not a radical shift from the current methods utilised by the automotive industry. The ability to maintain current process streams will make introducing the technology significantly more appealing to manufacturers and allow the clamshell method to be adopted on an industrial scale.

4.3. Gripping and Transportation

When using automated systems during the transportation (or 'pick and place') of composite preforms during manufacture, the effectiveness of the robotic prehension tools (or 'grippers') utilised can have a significant impact on the cost and effectiveness of the manufacturing stream. When handling composite preforms, ingressive prehension tools are usually utilised, in the form of needle grippers, or astrictive techniques in the form of vacuum grippers [25].

Needle gripper penetration leads to fibre disruption, misalignment and even breakage [31, 27], and the complex design of these grippers means a significant cost. Vacuum grippers tend to be two to three orders of magnitude cheaper than needle gripping systems. However, a porous preform requires the suction to be constantly on, as a high flowrate is required. These high flowrate systems are in contrast to normal low airflow, large underpressure systems, and are thus significantly larger and more complex [27]. This is problematic from a cost basis, with more advanced vacuum systems and constant power drain, and on a noise basis. The noise of multiple always-on vacuum grippers handling dry composite preforms can be so loud as to make the factory floor unbearable to work on for long periods and even hazardous to health. As such, there currently exists no commercially available gripper system for fibrous preforms that does not negatively impact upon the manufacturing process in a typical RTM environment [26].

Using the clamshell manufacturing technique, the need for expensive and complicated needle grippers is removed, with simple vacuum grippers utilised. The suction cup is attached directly to the shell, a non-porous material, thus the airline need only be activated for a very short time whilst suction is achieved, and can be turned off again, giving a significant saving in cost and lowering of noise levels. The risk of preform damage is eliminated, and fibre pull-out is prevented by the shell.

5. Experimental Methodology

All Laboratory scale experiments were carried out to investigate transportation, handling and resistance to damage and deformation (alongside a traditional dry fibre preform), to understand any potential improvements which may be offered.

5.1. Materials

A triaxial carbon NCF fibre from Formax (FCIM357-PB [C24k, 750, -45/0/+45, A]) was preformed to a 6-ply thickness, providing a final preform lay-up of $[-45/0/+45]_2$.

Two thermoplastic polymers were used for shells: Acrylonitrile Butadiene Styrene (ABS) and High Impact Polystyrene (HIPS), in the form of 1mm sheets. These can be vacuum formed, allowing for simple fabrication of 3D clamshell preforms. HIPS provides good formability characteristics as a demonstrator, whilst ABS offers sufficient mechanical performance to be of future interest.

5.2. Sample Manufacture

Three types of preform were manufactured:

1. 'Traditional' dry fibre preform. A spray adhesive was used as an analogue to traditional binder, to form a flat preform. The NCF itself is stitched together to hold it in place. The preform planar dimensions are 65mm x 35mm.
2. Flat 'clamshell' preform. Dry fibre was placed inside two protective polymer layers to form the clamshell. The fibre dimensions are the same as the dry preform manufactured above, with an additional polymer 'flange' present around the exterior. The sheets were either vacuum formed around the fibre to a flat shape, or flat sheets were heat-sealed around the fibre.
3. 3D clamshell preform. The dry fibre was placed between two layers of HIPS and vacuum-formed utilising an MDF tool, with base measurements of 670x400mm, a height of 70mm and a slope angle of 30°. The final part produced is shown in Figure 3.

5.3. Robotic Handling

Following the fabrication of the samples, a number of demonstrations were undertaken utilising an ABB IRB 140 robot head. This work was undertaken to show the clamshell's effectiveness under automated handling and gripping conditions.

5.3.1. Pick-up test

A number of pick-up, move, and drop tests were undertaken. Initially, both the traditional preform and the shell were picked-up and moved at a steady speed, being dropped at the final position. The head moved at three different speeds: 100 m/s, 500mm/s and 800mm/s. This was to determine the reliability of the vacuum grip for each preform type, at an initial slow speed to allow observation and to assess the effects at increased speed on the preforms. This movement consisted of: lowering to collect the preform, vacuum on, head up with preform attached, and translational movement 1.5m in an arc with the preform held flat. This was then reversed, returning the preform to the initial position. This was then carried out 10 times at the fastest speed for both the traditional binder preform and the clamshell, to understand if repeated gripping and releasing on either causes problems or positional drift from the desired start and end position.

5.3.2. Positional test

The robot head's various axes of movement were utilised in order to twist and tilt the preforms through a full arc of movement. This allowed the clamshell to be assessed in comparison to the traditional preform part, for both reliability of grip and for deformation throughout the movement arc. This movement consisted of a full 180° arc about one axis of movement for the head, followed by a 90° arc around a perpendicular axis. A further 180° arc followed, after which the head then returned the preform to its flat starting orientation, at which point it was shaken back and forth several times to assess the effectiveness of the attachment, before being placed back on the starting station.

5.3.3. Drape and deformation

Further drape and deformation trials were undertaken, demonstrating the effectiveness of the grippers when positioned in the centre traditional preform and the shell structure. A single gripper was used. Needle grippers were also trialled for the central gripping of the traditional preform, and both their effectiveness and the damage caused were assessed. The preforms were taken through the same movements as detailed in Section 5.3.2.

5.3.4. 3D shell movement

The three-dimensional clamshell was tested for basic movement and manipulation by the robot head. The aim of this was to demonstrate that, utilising the clamshell, movement of preforms throughout an assembly line can be achieved irrespective of preform shape. The preforms were taken through the same movements as detailed in Section 5.3.2.

5.4. Resistance to deformation

Both flat preforms were subjected to 'drop tests'. This was to simulate the effects of dropping during manual handling or failure of robot gripping heads. Whilst these simple drop tests did not provide quantitative data on the mechanical performance of the shells or traditional preforms under impact loading, they were undertaken with the aim of giving some qualitative understanding of the performance of each in a simulated manufacturing environment, where the potential for such random and unexpected incidents to occur is significant. The drops took place at 4 different heights: 0.5m, 1m, 1.5m and 2m. The aim was to land the preform upon an edge or corner, as this is most likely to induce damage or defects.

6. Results and Discussion

6.1. Sample Manufacture

The 'traditional' dry fibre preform was more stable than initially expected. The triaxial fibre configuration was tightly stitched together and the heavy-duty spray adhesive that was used gave a stiffer preform. However, it should of course be noted that this form of adhesive would be completely unsuitable if this preform was being manufactured as part of a full fabrication process, as it would leave the preform completely unsuitable for infusion. Therefore, this should be considered simply a demonstrator piece for the purposes of automated handling.

Both flat clamshell preforms were manufactured to an acceptable standard for this initial trial work, however each method had its own limitations. Simply sealing a flat ABS sheet with a hot tool to form sealed flanges around the preform gave a reasonable result. However, some warping was present due to the heating of the plastic, meaning a perfectly shaped final piece was not manufactured.

By contrast, the flat preform manufactured using the HIPS material and the vacuum forming method better shaped around the preforms. This could be seen as a better representation of the final clamshell design as envisioned during the formulation of this manufacturing process. Especially of note is the good quality finish on the tool side and the shaping of the shell around the edges of the preform. However, this shell also has its limitations, due to being formed on a large flat aluminium tool-plate, and thus a lack of proper vacuum airlines has led to a slight deformation of the non-tool surface in the form of small amounts of trapped air. Once more, this is a process to be further refined in future work.

Fig. 3. 3D clamshell as manufactured

The 3D shell was formed with perhaps the greatest level of success. Due to the semi-porous MDF tool used, good airflow was achieved, and the clamshell preform formed to shape well. The fibre is readily visible through the non-tool surface, with some minor plastic wrinkling on this surface being visible. By contrast, the tool surface formed well, with slight bridging across the two inner curves, demonstrating the need for designed-in radius when utilising corners in the fibre direction. Figure 3 shows both surfaces of the three-dimensional part as formed, to give a view of the finish achieved.

6.2. Resistance to deformation

6.2.1. Pick-up test

The initial pick-and-place tests demonstrated some of the issues previously noted for the use of automated handling of dry fibre preforms. During the initial slow, translational-movement tests, obvious bowing of the preform and deformation of fibres were clearly present. This is in contrast to the clamshell, whereby no obvious defects could be observed during movement. The flat clamshell chosen for testing on the robot was that manufactured utilising the HIPS material, as the tool surface provided an excellent finish for the vacuum grippers, whilst the lower quality thermoplastic was of no consequence during this section of testing.

Upon operating at full speed for 10 repeated cycles, there was notable positional drift present in the final position of the dry fibre preform. This was offset from the starting position by 8.5mm and 6mm in each planar direction. A very small amount of rotation was visible, but this could be considered negligible as it was under 2°. Contrastingly, the clamshell preform, whilst also having a negligible twist present in the final position after 10 trials, had less than 1mm deviation from the starting position. It can be seen that this is due to the reliability of the surface and position that the grippers would attach to each time, as opposed to the fibrous preform which would deform slightly on each cycle and thus each time be gripped in a different position.

6.2.2. Positional test

Problems with deformation whilst moving the traditional fibre preform became even more apparent during the more complicated movements of the second set of tests. Once the preform was moved out of simple flat, translational movement and rotated around the robot head more severe fibre draping and geometric deformation became obvious. This contrasts with the significantly more rigid clamshell preform, which held its shape with greater success. These two contrasting results can be seen in Figure 4, showing the movement arc paused at the same time for both preform types to view the differences.

Clear deformation was visible on the surface of the traditional fibre preform when vacuum grippers were utilised. This is a well noted and documented issue, with regards to automated handling of composite preforms. Indeed, this is why smaller diameter vacuum grippers are often utilised in comparison to those used here. However, as previously noted, these still cause surface deformation and geometric defects, whilst simultaneously allowing for less manoeuvrability of the part by the robotic head.

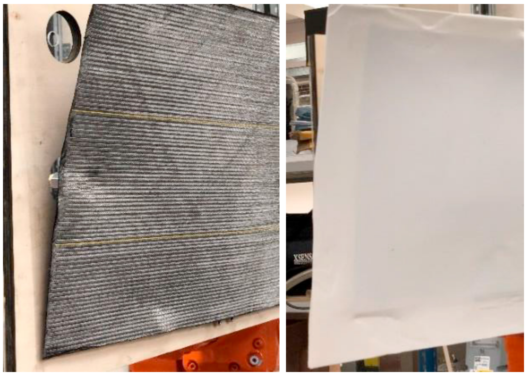

Fig. 4. Traditional dry fibre preform (left) and clamshell preform (right). The traditional preform has lost its shape and begun to bend due to movement and the gravitational effects in this position, whilst the clamshell preform has held its shape

Despite the expectation that some level of defect would be present on the fibrous preform due to the vacuum grippers, the final level of deformation was alarming and severe. Domes of fibre were formed by the suction of the grippers, measuring 4mm at their peak. This is outside acceptable geometric tolerances of most automotive parts in the thickness dimension, and thus leads to obvious problems further along the manufacturing stream. These defects are shown in Figure 5, during and following the positional trials.

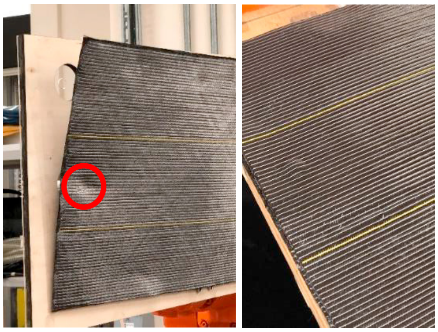

Fig. 5. Traditional dry fibre preform in-situ with vacuum grips (left) and upon removal from vacuum grips (right)

By contrast, these problems were not present at all with the clamshell preforms. The vacuum force and suction utilised in order to grip the shells did not deform them. This demonstrates one of the clear benefits of the clamshell concept: the structural rigidity, and thus geometric tolerances of the preform is maintained during handling and transport. Further, the use of cheap vacuum grippers was sufficient, and there was little need to invest heavily in more expensive needle gripper systems in order to effectively move the shell.

6.2.3. Drape and deformation

Upon utilising a single central gripper for the movement path, the benefits of utilising the clamshell approach over traditional binder became even more apparent. The clamshell moved throughout the entire movement path with little to no visible deformation. In contrast, the traditional preform began to bend severely back towards itself. This happened even across the axis of the fibre direction, where the preform is stiffest. The bending was so great that the preform began to contact the final placement table as it approached, meaning that the positional placement accuracy was lost. An example of how the two preform types did and did not deform is shown in Figure 6.

Needle grippers were also utilised as a central gripping technique for the traditional preform. Whilst these did not cause surface geometry deformation in the same way as the vacuum grippers, there was notable fibre misalignment present following the use of the grippers. Further, the same problems with preform bending were present here, due to the use of a single central gripper.

Fig. 6. Dry fibre preform (top) and clamshell preform (bottom) gripped using 1 central gripper.

6.2.4. 3D shell movement

The 3D clamshell preform was also moved around the full arc of movement without issue or deformation. Whilst this was simply utilised as a demonstration piece, rather than in comparison to a traditional bound preform, the ability to move this preform without issue or deformation is promising for potential future work utilising the clamshell concept. This is especially true when considering the quick time and ease this basic demonstrator piece was fabricated with.

6.3. Resistance to deformation

Both the traditional and clamshell preforms performed well at the lower drop heights of 0.5m and 1m, with no deformation visible. However, at drop heights of 1.5m and 2m, distinct changes in the geometry of the traditional preform were visible after impact. After the 1.5m impact, it was formed back into shape, and then dropped onto the other edge for the final 2m impact, with the results of these impacts shown in Figure 7. By contrast, the clamshell preform suffered no issues or geometric failures up to a drop height of 2m, even when landing on the corner or edge of the preform.

Fig. 7. Deformation suffered by fibrous preform during drop test at 1.5m (top) and 2m (bottom)

It is noted that these tests do not represent a thorough demonstration on the effects of impact on both types of preform. Indeed, further work should be carried out to fully characterise both a traditional preform and a clamshell preform with regards to their resistance to impact across the entire part. However, these tests are included here to give an early indication of the potential that may be offered by the clamshell with regards to protection of the shell when dropped during handling.

7. Conclusions

This work was undertaken as initial proof-of-concept work to assess the feasibility and promise of utilising the clamshell structure as a transportation shell during the implementation of a full, clamshell-based manufacturing process stream. As initial work, very few quantitative results can be extracted from the experiments undertaken. Instead, more visual and qualitative observations have been gleaned, in order to assess whether the concept is both feasible, and perhaps more crucially, useful, with regards to the transportation of composite preforms as part of a high-volume manufacturing process.

It can be judged that promising observations can indeed be made from the trials undertaken here. A lack of introduction of surface and geometric defects, alongside the ease of gripping of the shells and transportation at high speed by autonomous, robotic systems indicates that the clamshell concept has significant potential to be able to replace metallic sheets in this part of the automotive/high-volume manufacturing stream without significant deviation from current techniques and equipment used, or introduction of many of the problems traditionally associated with the automated handling of fibrous preforms.

Whilst the numerous positive observations noted throughout Section 6 do show potential for this work to be taken further, it must be noted that this work is preliminary and thus no full characterisation of the transportation system and benefits have yet been undertaken. However, due to the numerous potential benefits laid out in Section 5, this is a large body of further work which should indeed be pursued. With full realisation of the potential laid out and demonstrated here, high-volume manufacturing of structural composite parts for the automotive industry has the potential to be realisable in a shorter time frame than is perhaps currently assumed. The introduction of this relatively fast and inexpensive manufacturing method has the potential to allow for the lighter vehicle structures required to meet the ever-increasing climate and emission issues that currently face the automotive industry.

Acknowledgements

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